Chapter 4

Gravitational Forces

Army aircrew members must understand gravitational forces and the physiological responses of the body to them in the aviation environment. This is especially true with the advent of the newer high-performance helicopters such as the UH-60 Black Hawk and the AH-64 Apache. This chapter discusses the physics of motion and acceleration, and covers the types and directions of accelerative forces and their influences and effects. It also discusses deceleration and, more importantly, the crash sequence and how aircraft design offers protection from crash forces. Aircrew members must have a fundamental, but thorough, understanding of the accelerative forces encountered during flight and their relationship to the human body.

TERMS OF ACCELERATION

4-1. Several terms are used in discussing acceleration. Those most commonly used are speed, velocity, inertial force, centrifugal force, and centripetal force. These terms are defined in the glossary.

TYPES OF ACCELERATION

4-2. Flight imposes its greatest effects on the body through the accelerative forces applied during aerial maneuvering. In constant speed and straight-and-level flight, aircrew members encounter no human limitations. With changes in velocity, however, they can experience severe physiological effects. Acceleration is the rate of change in velocity and is measured in Gs. The aviator needs to understand where and how accelerative forces—linear, radial or centripetal, and angular—develop in flight.

LINEAR ACCELERATION

4-3. This type of acceleration is a change in speed without a change in direction. It occurs during takeoffs and changes in forward air speed. This type is also encountered when speed is decreased (Figure 4-1).

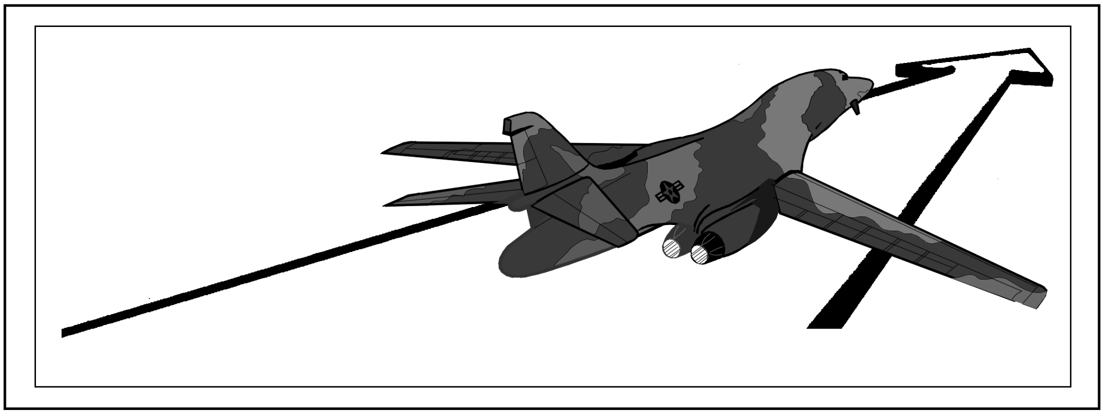

Figure 4-1. Linear Acceleration

RADIAL, OR CENTRIPETAL, ACCELERATION

4-4. This type of acceleration can occur in any change of direction without a change in speed. Crew members may encounter this type of acceleration during banks, turns, loops, or rolls (Figure 4-2).

Figure 4-2. Radial, or Centripetal, Acceleration

ANGULAR ACCELERATION

4-5. This type of acceleration is complex and involves a simultaneous change in both speed and direction. A good example of this is an aircraft that is put into a tight spin. For practical purposes, angular acceleration does not pose a problem in understanding the physiological effect of accelerative forces. Its principal effects are important, however, because they produce many of the disorientation problems encountered in flight (Figure 4-3).

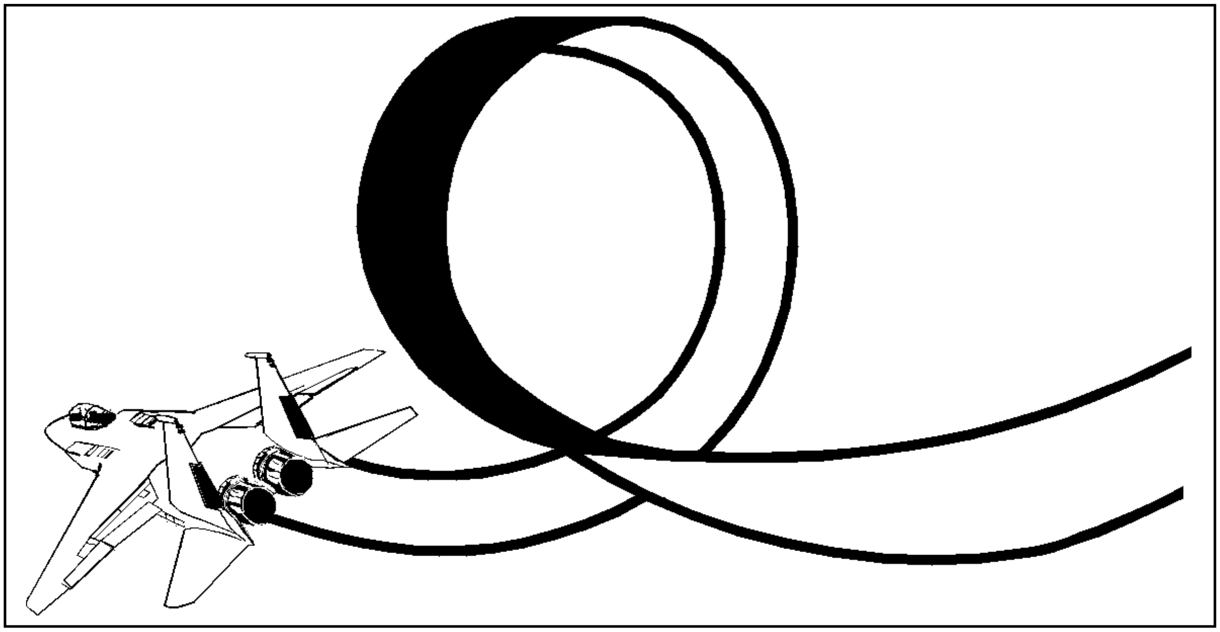

Figure 4-3. Angular Acceleration

GRAVITATIONAL FORCES

4-6. Newton's three laws of motion describe the forces of acceleration. The first describes inertia, stating that a body remains at rest or in motion unless acted upon by a force. Newton's second law of motion states that, to overcome inertia, a force (*F*) is required, the result of which is proportionate to the acceleration (*a*) applied and the size of its mass (*m*); that is, $F = ma$. Newton's third law states that for every action (acceleration centripetal force), there is an equal and opposite reaction (inertial centrifugal force).

4-7. The gravitational force (G-force) and the direction in which the body receives that force are important physiological factors that affect the body during acceleration. As shown in Figure 4-4, G-forces can affect the body in three axes: Gx, Gy, and Gz. The physiological effects of prolonged acceleration depend on the direction of the accelerative (centripetal) force and, consequently, on how the inertial force acts upon the body. The inertial (centrifugal) force is always equal to, but opposite, the accelerative force. The inertial force is the most important physiologically. The various G-forces are explained below:

- Positive G, or + Gz, acceleration occurs when the body is accelerated in the headward direction. The inertial force acts in the opposite direction toward the feet, and the body is forced down into the cockpit seat.
- Negative G, or –Gz, acceleration occurs when the body is accelerated footward. The inertial force is toward the head, and the body is lifted out of the cockpit seat.

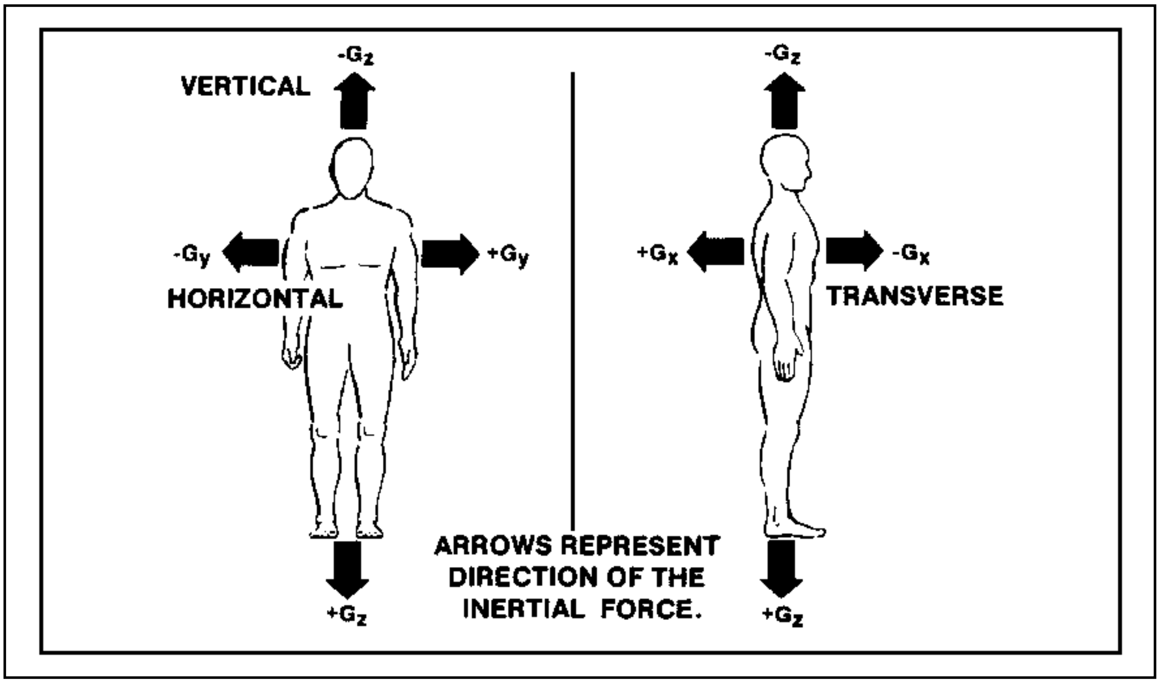

Figure 4-4. G-Force

- Forward transverse G, or +Gx, acceleration occurs when the accelerative force acts across the body in a chest-to-back direction. The G acceleration is experienced during acceleration.
- Backward transverse G, or –Gx, acceleration occurs when the accelerative force acts across the body in a back-to-chest direction. The –Gx acceleration is experienced during deceleration.
- Right- or left-lateral G, or +/–Gy, acceleration occurs when the accelerative force impacts across the body from a shoulder-to-shoulder direction.

FACTORS AFFECTING ACCELERATIVE FORCES

4-8. To determine the effects of accelerative forces on the human body, crew members must consider several factors. These factors include intensity, duration, rate of onset, body area and site, and impact direction.

INTENSITY

4-9. In general, the greater the intensity, the more severe are the effects of the accelerative force. However, intensity is not the only factor that determines the effects.

DURATION

4-10. The longer the force is applied, the more severe are the effects. Crew members can tolerate high G-forces for extremely short periods and low G-forces for longer periods. In general, the longer the force is applied, the more severe the effects. A force of 5 Gs applied for 2 to 3 seconds is usually harmless, but the same force applied for 5 to 6 seconds can cause blackout or unconsciousness. In ejection seats, pilots can tolerate a headward acceleration of 15 Gs for about 0.2 second without harm but will become unconscious when the same force is applied for 2 seconds. A force of 40 Gs received intermittently for fractions of a second during a crash landing is tolerable; if applied steadily for 2 to 3 seconds, the same force is fatal. The body can absorb, without harm, high G-forces applied for extremely short durations.

RATE OF ONSET

4-11. The rate of onset of accelerative or decelerative forces plays a part in the effects experienced. When an aircraft decelerates gradually, as in a wheels-up landing, the decelerative forces are exerted at a rather slow rate. Generally, when the rate of application is higher, such as when an aircraft decelerates suddenly during an accident, the effects are more severe. When an aircraft impacts vertically, the stopping distance is considerably shorter and the rate of application of accelerative forces is many times greater. The rate of application is often slowed down in helicopter crashes by the spreading of the skids and the crumpling of the fuselage, giving the body 3 or 4 extra feet in which to decelerate. Therefore, the distance, as well as the time, is an important factor in acceleration or deceleration. The shorter the stopping distance, the greater the G-force.

BODY AREA AND SITE

4-12. The size of the body area over which a given force is applied is important; the greater the body area, the less harmful are the effects. The body site to which a force is applied is also important. The accelerative effect of a given force, such as a blow to the head, is much more serious than the same force applied to another part of the body such as the leg.

IMPACT DIRECTION

4-13. The direction from which a prolonged accelerative force acts on the body also determines the physiological effects that occur. The body does not tolerate a force applied to the long axis of the body (Gz) as well as it does a force applied to the Gx axis (Figure 4-5).

PHYSIOLOGICAL EFFECTS OF LOW-MAGNITUDE ACCELERATION

4-14. The physiological effects of low-magnitude acceleration are the result of the inertial centrifugal force and the increased weight of the body and its components. Low-magnitude acceleration is described as Gs in the range of 1 to 10 with prolonged time of application lasting for at least several seconds. During aircraft maneuvers, the main part of the body affected by excessive G-forces is the cardiovascular system. The skeleton and soft tissues of the body can withstand such stress without problems. The circulatory system, however, consists of elastic blood vessels; to perform properly, the system needs a well-defined blood pressure and volume. Excessive gravitational forces, such as those experienced in prolonged acceleration, can disrupt the normal circulatory function.

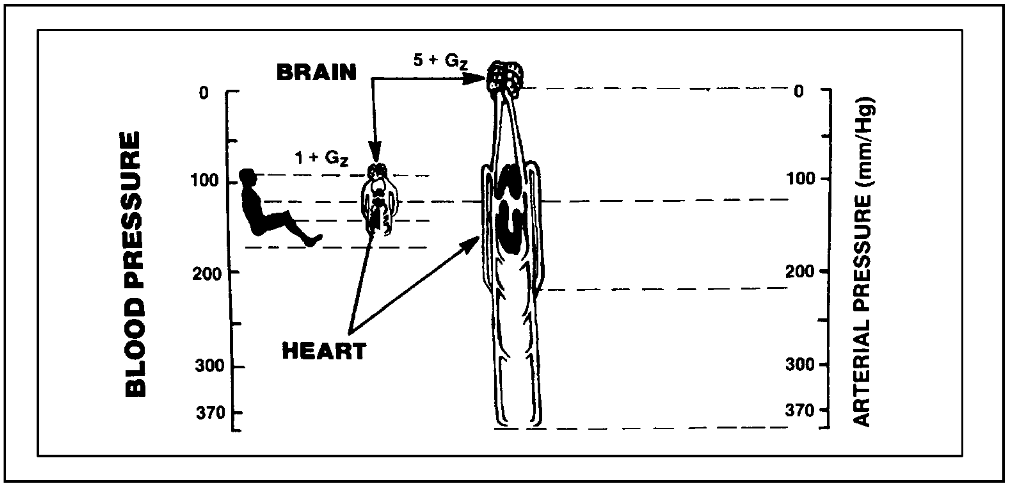

Figure 4-5. Impact Direction

PHYSIOLOGICAL EFFECTS OF +GZ ACCELERATION

4-15. Positive Gz is acceleration in a headward direction such as the centripetal force experienced in a turn. The aircrew member is more aware of the centrifugal (inertial) force, which acts in the opposite direction, toward the feet. Crew members experience this force during pullout from a dive or execution of a high, banking turn.

4-16. During a maneuver that produces +Gz, the weight of the body increases in direct proportion to the magnitude of the force. For example, a 200-pound person weighs 800 pounds during a 4-G maneuver. Normal activities are greatly curtailed, and the person is pushed down into the seat. The arms and legs feel heavy, the cheeks sag, and the body becomes incapable of free movement. In fact, a pilot cannot escape unassisted from a spinning aircraft if the magnitude of the force exceeds 2 to 3 +Gz. This is the primary reason for the adoption of the pilot’s ejection seat.

4-17. During a +Gz maneuver, the internal organs of the body are pulled downward. The increased weight of the internal organs pulls the diaphragm down, increases the relaxed thoracic volume, and disturbs the mechanics of respiration.

4-18. Comparing the body to a long cylinder helps explain the effects of a +Gz maneuver on the arterial blood pressure. In a seated individual, the heart lies approximately at the junction of the upper and middle thirds of the cylinder. The head and brain (the structures most sensitive to decreased blood pressure) are at the upper end of this vertical cylinder and about 30 centimeters from the heart. When a force of 5 +Gz is exerted on the body, a standing blood column of 30 centimeters exerts a pressure of 120 mm/Hg upon its base. Because this pressure is equal to the normal arterial systolic blood pressure, it exactly balances out the arterial pressure and causes the blood profusion of the brain to cease. Unconsciousness can result when a force of 5 +Gz is applied to the body. Figure 4-6 shows the effects of 1 +Gz to 5 +Gz conditions.

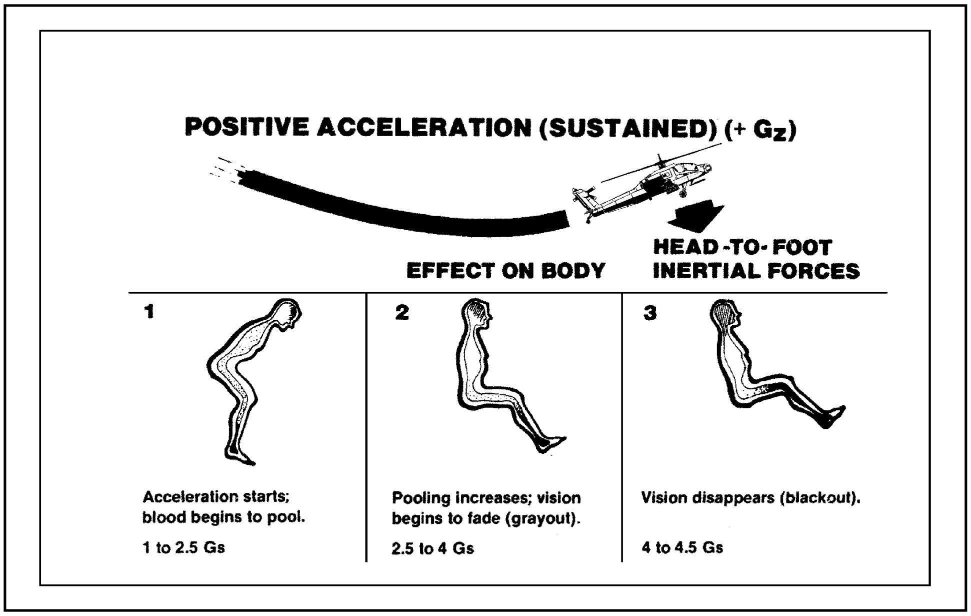

Figure 4-6. Positive Acceleration

4-19. At about 4 +Gz—the point at which vision is completely lost before a loss of consciousness—blackout occurs. Static intraocular pressure is about 20 mm/Hg. When a positive G-force is sufficient to reduce the systolic arterial blood pressure in the head to 20 mm/Hg, the intraocular pressure causes the collapse of retinal arteries. The retina ceases to function as the blood supply fails, and the vision narrows from the periphery. At about 4 to 4.5 Gz, vision disappears and blackout occurs. When the force reaches about 5 +Gz, cerebral blood flow stops and unconsciousness ensues. Therefore, the sequence of events following exposure to +Gz is the dimming of vision, blackout, and then unconsciousness.

4-20. The effects described above are usually progressive, as shown in Figure 4-6. In relaxed subjects in the human centrifuge, for example, the first symptoms from increased +Gz forces occur at 2.5 to 4 +Gz and involve a graying or dimming of the visual fields. At slightly higher accelerations (4 to 4.5 +Gz), blackout occurs and individuals can no longer see although they remain conscious. The retinal arteries have collapsed, but some blood still flows through the blood vessels of the brain. At 4.5 to 5 +Gz, unconsciousness occurs.

4-21. Blood pools in the lower extremities, and there is a relative loss of blood volume and blood pressure to the brain. Stagnant hypoxia and hypoxic hypoxia, caused by unoxygenated blood from impaired respiration, also occur. Oxygen saturation of the blood can fall from the normal 98 percent to 85 percent during an exposure of 7 +Gz for 45 seconds.

4-22. With the loss of blood pressure and the hypoxic state combined, it may take up to one minute following the end of acceleration for an individual to recover. After regaining consciousness, the crew member may still experience a period of disorientation and loss of memory for some time.

4-23. Although tolerance limits to G-forces are relatively constant from one person to another, certain factors decrease or increase an individual's tolerance to +Gz. These are the decremental and incremental factors.

DECREMENTAL FACTORS

4-24. Any factor that reduces the overall efficiency of the body, especially the circulatory system, causes a marked reduction in an aircrew member's tolerance to +Gz. Loss of blood volume, varicose veins, and decreased blood pressure (chronic hypotension) can affect the circulatory system. Self-imposed stress, such as that caused by alcohol abuse, also affects the aircrew member's tolerance to +Gz.

INCREMENTAL FACTORS

4-25. The L-1 maneuver is an Anti-G Straining Maneuver (AGSM) that increases the crew member's G-tolerance. For protection that does not overstress the larynx, crew members can use the L-1 maneuver. In this maneuver, crew members maintain a normal upright sitting position, tense skeletal muscles, and simultaneously attempt to exhale against a closed glottis at two- to three-second intervals. Although the L-1 maneuver was developed by the Air Force for its fighter pilots, rotary-wing crew members experiencing gray-out conditions will also benefit from this maneuver.

PHYSIOLOGICAL EFFECTS OF –GZ ACCELERATION

4-26. When the accelerative force acts on the body in a direction toward the feet, as would be experienced in a rapid descent, –Gz occurs. In this case, the accelerative (centripetal) force acts toward the axis of the turn. Actually, –Gz does not present a great problem in military flying. Because it is an uncomfortable experience, pilots tend to avoid it.

4-27. Negative acceleration, inertial force applied from foot to head, causes a sharp rise in arterial and venous pressures at the head level. The increased pressure within the veins outside the cranial cavity may be sufficient to rupture the thin-walled venules (small veins). The intracranial venous pressure also rises, but it is counterbalanced by an accompanying rise in intracranial cerebral spinal-fluid pressure. Therefore, there is little actual danger of intracranial hemorrhage or cerebral vascular damage as long as the skull remains intact. Hemorrhages within the eye present the primary source of damage from –Gz. Distension of the jugular veins and veins of the sinuses and conjunctiva is caused by –Gz.

4-28. Sudden acceleration producing a force of 3 –Gz reaches the limit of human tolerance. When such a force is applied, venous pressure of 100 mm/Hg develops and causes small conjunctival bleeding areas and marked discomfort in the head region.

4-29. During –Gz maneuver, redout may be experienced (Figure 4-7). This phenomenon occurs when the gravitational pull acts on the lower eyelid, causing the lower eyelid to cover the cornea. The constant pull of gravity on the lower eyelids tends to weaken their muscles.

4-30. If sufficiently prolonged, a gravitational pull in the foot-to-head direction also leads to eventual circulatory distress. Pooling of blood occurs in the head and neck regions, which then leads to a passage of fluid from the blood to the tissue spaces of the head and neck. In addition, the return of blood to the heart becomes inadequate because of the loss of the effective blood volume. Therefore, blood stagnates in the head and neck. The cerebral-arterial and venous pressure differential is inadequate to sustain consciousness.

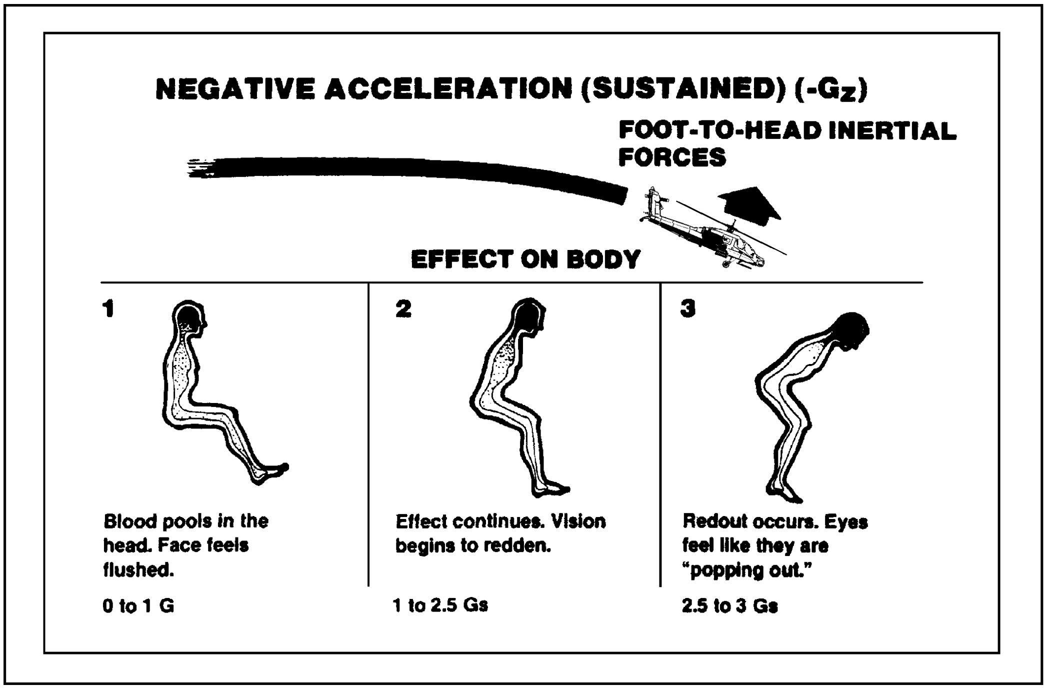

Figure 4-7. Negative Acceleration

PHYSIOLOGICAL EFFECTS OF +/–GX ACCELERATION

4-31. Transverse-G occurs when the accelerative force impacts across the body at right angles to the long axis. The inertial (centrifugal) force will also cross the body—in the opposite direction. Aircrew members undergo mild transverse acceleration during takeoffs and landings. The physiological effects of transverse acceleration are important in manned space missions; they are experienced during initial lift-off and reentry.

4-32. Individual are more tolerant of forces received in the +/–Gx axis than of those received in the other axes because transverse Gs interfere very little with blood flow. Extreme values of transverse G (12 to 15 +/–G) acting for five seconds or more can displace organs or shift the heart's position and, thereby, interfere with respiration.

4-33. At levels above 7 +G, breathing becomes harder because of the effect on the chest movement. Some individuals, however, have withstood levels of 20 +G for several seconds with no severe difficulty.

PHYSIOLOGICAL EFFECTS OF +/–GY ACCELERATION

4-34. The human body has minimal tolerance to Gy (right- or left-lateral) acceleration. Most aircraft do not normally apply significant accelerative forces in the lateral direction. Therefore, this type of G-force is of little significant during low-magnitude acceleration.

PHYSIOLOGICAL EFFECTS OF HIGH-MAGNITUDE ACCELERATION AND DECELERATION

4-35. High-magnitude acceleration and deceleration affect aircraft accident survivability. High-magnitude acceleration occurs when acceleration exceeds 10 Gs and lasts for less than one second. The effects of high-magnitude acceleration are usually the result of linear acceleration. The terms acceleration and deceleration (negative acceleration) are synonymous when used to describe the forces encountered in aircraft crashes, ejection-seat operations, and parachute-opening shock.

HIGH-MAGNITUDE ACCELERATION

4-36. Adverse effects and injury result from the abruptness and magnitude of forces. Other factors are the body area to which the force is applied and the extent of distortion in shearing, compressing, or stretching body structures. The severity of effects progresses from discomfort, incapacitation, minor injury, and irreversible injury to lethal injury. A thorough examination of the cause of the injury and the effects on the body is essential for determining survival limits and for devising protective and preventive measures.

HIGH-MAGNITUDE DECELERATION

4-37. Several factors cause the adverse effects of high-magnitude decelerative forces. These factors are the—

- Degree of intensity of the acceleration, known as the “peak G.”
- Duration of the “peak G” and the total time of the deceleration.
- Rate of application or rate of onset of the acceleration, known as the “jolt.” The jolt, expressed in feet per second or Gs per second, is the rate of change of acceleration or the rate of onset of accelerative forces.
- Direction or axis of force application that determines whether acceleration or deceleration occurs.

CRASH SEQUENCE

4-38. During the accident sequence, the aircraft occupants’ survival depends on three criteria. These criteria are the crash forces transmitted to the occupants, occupiable living space, and aircraft design features.

Crash Forces

4-39. The intensity of the decelerative force to which the body is subjected is not a single decelerative G; instead, crash forces produce a series of decelerations, at various G-loads, until all motion is stopped (Figure 4-8). In addition, these crash forces occur in all three axes (Gx, Gy, and Gz) at the same time (Figure 4-9). The tolerance limits to high-magnitude deceleration vary with the duration of the force and direction. The human body, however, is far more vulnerable to injury when exposed to a series of high-G shocks in all three axes. As Figure 4-9 shows, the human body can withstand these forces only for an extremely short time (less than 0.1 second). If this is exceeded, injury or death occurs.

Occupiable Living Space

4-40. The occupants' living space influences survivability and must not be compromised either by failure of the airframe or by possible penetration of the cabin area by outside objects. If either human-tolerance limits to decelerative forces are exceeded or living space is lost, survivability in an accident sequence decreases significantly. To provide maximum protection to aircrew members during an accident, certain design features can be built into an aircraft to absorb crash forces. The UH-60 (Black Hawk) shows that a crashworthy design is possible (Figure 4-10).

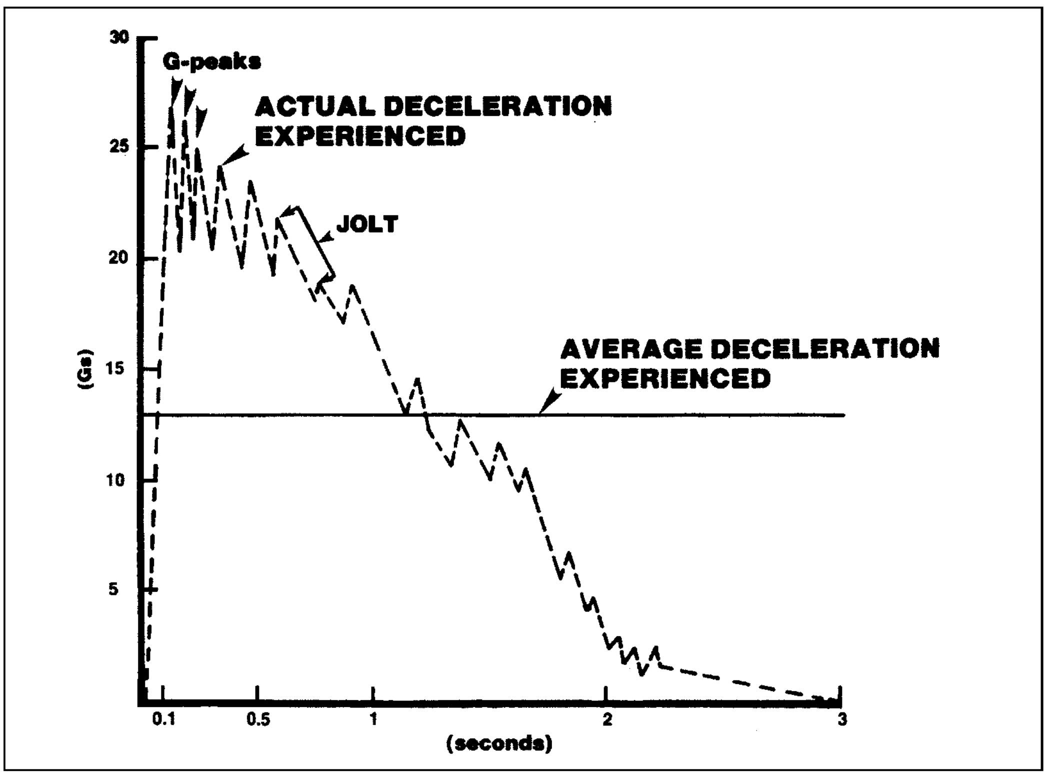

Figure 4-8. Decelerative Forces Experienced During an Accident of Three-Second Duration

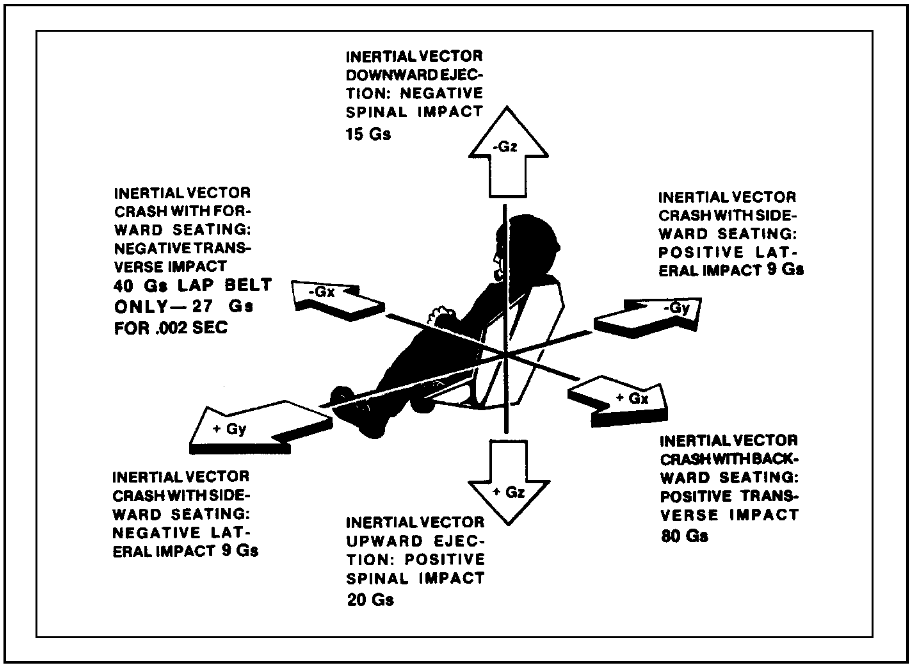

Figure 4-9. Human-Tolerance Limits to Whole-Body Impact (Duration 0.1 Second)

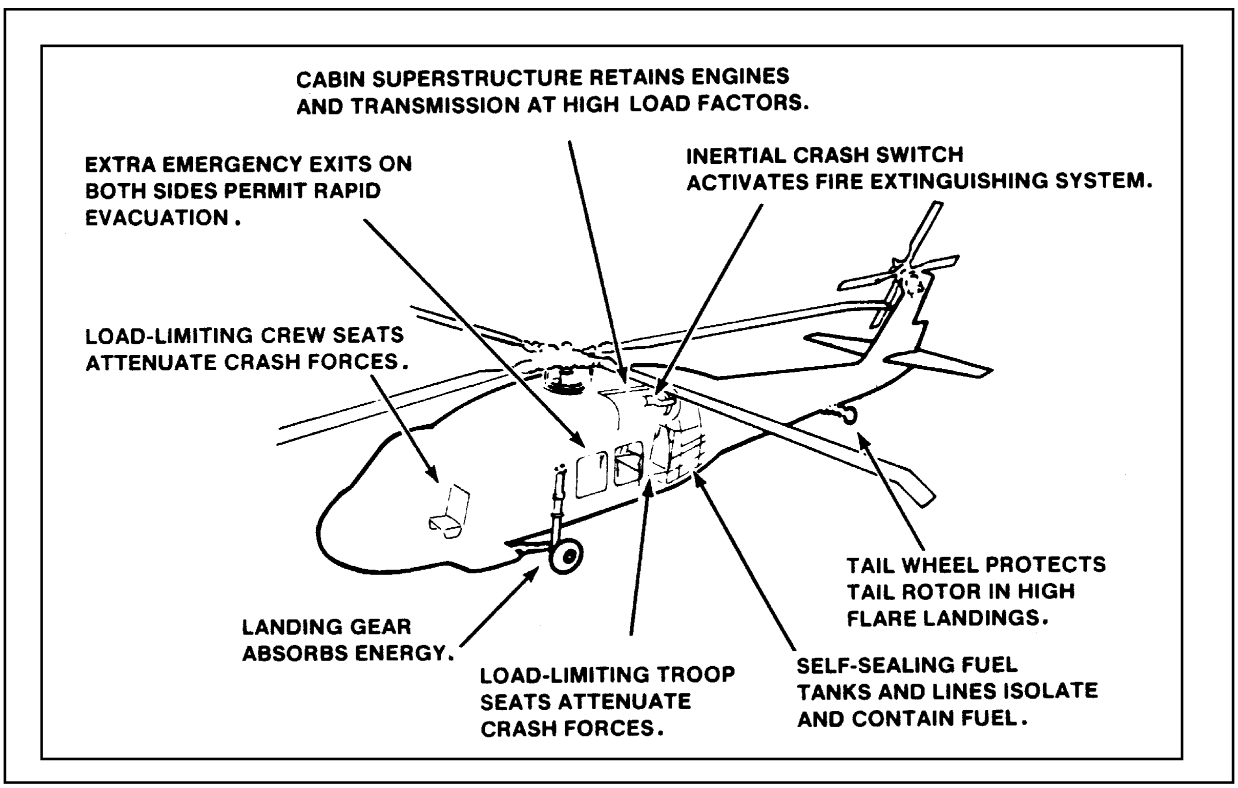

Figure 4-10. Crashworthy Design Features of the UH-60 (Black Hawk)

Aircraft Design Features

4-41. Design features that aid crash survival are commonly referred to as the CREEP factors. These factors are explained below:

- **C—Container.** An aircraft must be designed with an effective protective shell around the occupants. Its maximum structural and component weight should be below the occupants to reduce cabin crushing by inertial loading. The airframe should contain crushable material to attenuate crash forces before they are transmitted to the crew members. Fuel cells (tanks) should be of crashworthy design and be protected by the airframe to prevent outside objects from penetrating them.
- **R—Restraint Systems.** Restraint systems should attenuate crash forces and protect the occupants in all conditions of flight. These systems should be comfortable to wear and not interfere with cockpit duties. The head is the most likely point of injury in an accident sequence; therefore, occupants should use shoulder harnesses to minimize upper-body motion. A failure in any part of the restraint system—seat, seat belt, or anchor points—results in a higher degree of exposure to injury.
- **E—Environment.** The cockpit and cabin area must be “delethalized” to include adequate equipment restraints for withstanding crash forces.
- **E—Energy Absorption.** With their energy-absorbing features, aircraft are designed to withstand disruptive forces. Some features are the aircraft undercarriage, landing gear, and seat design that deform during the accident sequence. These modify high-peak G-loads of short duration into more survivable G-loads of longer duration.
- **P—Postcrash Protection.** Two major postcrash factors must be considered: fire and evacuation. The crashworthy fuel system has drastically reduced the fire hazard in Army aircraft accidents. However, timely evacuation is still desirable. The timeliness in evacuating aircraft occupants who survive an impact is often governed by the adequacy of emergency exits. Other factors that enhance timely evacuation are convenience of location, ease of operation (the UH-1 cargo door window is a prime example), and adequacy of markings.

PREVENTIVE MEASURES

INCREASE THE AREA TO WHICH THE FORCE IS APPLIED

4-42. This is accomplished through a variety of methods. The HGU-56/P protective helmet distributes pinpoint pressure over a larger area and reduces the chance of head injury. Seat belts with shoulder harnesses distribute decelerative forces over a larger area of the body and help prevent hazardous contact with the cabin environment. Backward seating arrangements also distribute decelerative forces normally found in the accident sequence.

INCREASE THE DISTANCE OVER WHICH THE DECELERATION OCCURS

4-43. The built-in design features of the aircraft can absorb and dissipate much of the kinetic energy during the crash. These features increase the distance over which the deceleration occurs.

ALIGN THE BODY TO TAKE ADVANTAGE OF THE STRUCTURAL STRENGTH OF THE MUSCULOSKELETAL SYSTEM

4-44. The correct alignment of the body is a preventive measure that can be taken during a crash. Crew members can align the body to take advantage of the structural strength of the musculoskeletal system, especially during the accident sequence. The proper use of seat belts, the shoulder harness, or the crash position (with the body bent forward) ensures that the strongest parts of the body absorb the crash forces.